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THE ACT REFERENCE CATALOG

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ABSTRACT

The US Naval Observatory has completed the compilation of the ACT Reference Catalog, containing 988,758 stars covering the entire sky. The motivation behind the ACT was to provide accurate proper motions for the majority of the stars in the Tycho Catalogue. To do this, positions from new reductions of the Astrographic Catalogue (AC 2000) were combined with those of the Tycho Catalogue. The large epoch span between the two catalogs yields proper motions about an order of magnitude more accurate than those found in the Tycho Catalogue. The astrometric data contained in the ACT Reference Catalog include positions and proper motions and their corresponding errors. These are on the *Hipparcos* system (ICRS) for epoch J2000.0. Photometric and variability data from Tycho are included. In addition, cross-references to the Tycho, AC 2000, Bonner Durchmusterung (BD), Cordoba Durchmusterung (CD), Cape Durchmusterung (CPD), Henry Draper (HD), and *Hipparcos* catalogs are given. The ACT is now available at the international data centers and by contacting the authors via electronic mail.

Key words: astrometry—catalogs—reference systems—surveys

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1. INTRODUCTION

The success of the European Space Agency's *Hipparcos* satellite mission has led to the production of two important astrometric catalogs, Hipparcos and Tycho (ESA 1997). The former contains positions and proper motions of 118,218 stars accurate to about 1 mas at epoch J1991.25 and 1 mas yr^{-1}, respectively. Tycho contains nearly 1 million stars whose errors are close to 25 mas at J1991.25 and 25 mas yr^{-1} for positions and motions, respectively. The accuracies of the Tycho positions at the epochs of observation are better than most ground-based catalogs, and about an order of magnitude better than any other catalog of comparable size. However, the uncertainty in the Tycho proper motions rapidly degrades the positions for applications at other epochs. The US Naval Observatory (USNO) has several projects requiring precisions higher than those found in Tycho, such as the astrometric pipeline for the Sloan Digital Sky Survey (Gunn & Knapp 1993) and USNO CCD Astrometric Catalog project (Gauss et al. 1996). These requirements have necessitated our work on improving the Tycho proper motions. Others planning to use the Tycho data, such as those involved in the digitization and reductions of photographic surveys (Lasker 1993; Monet 1997), occultation

predictions, and Galactic kinematic studies, can also benefit from more accurate proper motions.

The proper motions can be improved by combining the Tycho positions either with new observations of Tycho stars or with older observations. Plans are underway for new astrometric-quality observations that will include all stars in Tycho (Zacharias 1998); however, results will not be forthcoming for a few years. Using older observations to improve the proper motions is currently the only method available. To adequately do this, the older positions must be reasonably accurate and include a large percentage of Tycho stars at a suitably early epoch. An obvious data set to use is the Astrographic Catalogue (AC), because of its positional quality, limiting magnitude, and epoch near 1900 (Eichhorn 1974). Using the data contained in the Astrographic Catalogue as first-epoch positions for improved Tycho motions was discussed as early as 1993 (Urban 1993; Röser & Høg 1993). New reductions of the Astrographic Catalogue measures have been completed and released under the name AC 2000 (Urban et al. 1998). The combined AC 2000 and Tycho have been released as the ACT (AC + Tycho) Reference Catalog. This paper briefly discusses the AC 2000, Tycho Catalogue, computation of proper motions, and characteristics of the ACT Reference Catalog.

2. ASTROGRAPHIC CATALOGUE AND AC 2000

The Astrographic Catalogue was an international program conceived in 1887 and designed to photograph and measure the positions of all stars brighter than visual magnitude 11.0. Since observing and measuring the 22,000 plates needed to cover the sky was too labor-intensive for any one observatory to undertake, the task was spread among several observatories, each photographing and measuring stars between two parallels of declination. In total, 20 observatories participated in the data gathering, and the sky was sectioned into 22 zones. By the conclusion of the project, positions of 4.6 million stars had been measured, many as faint as 13th magnitude. Although the AC plates cover a wide range of epochs, the median epoch is 1904, and 90% of the plates were taken before the end of 1920.

Measures contained in the Astrographic Catalogue have recently been reduced at the USNO and combined to form an all-sky catalog called AC 2000. To compile the AC 2000, each of the 22 zones making up the Astrographic Catalogue was reduced independently, using the Astrographic Catalog Reference Stars (ACRS; Corbin & Urban 1988, 1990). The measures of each zone were analyzed for tilt, radial and tangential distortions, coma, magnitude equation, and nonsymmetric field distortions. Following this analysis, reductions of each plate were made to transform the image measures to equatorial coordinates. After these reductions, the data were placed on the *Hipparcos* system and the magnitudes were converted to be close to those of the Tycho *B* data. The resulting data were then combined into the final catalog. Detailed information on the reduction methodology and input data can be found elsewhere (Urban et al. 1998).

Although positional accuracies contained in the AC 2000 vary from zone to zone and star to star, most are between 150 and 300 mas at the mean epochs of observation. These have been computed by analyzing images of the same stars on overlapping plates. The early epochs and good accuracies make the positions in the AC 2000 extremely valuable for determining proper motions when combined with modern observations.

3. TYCHO CATALOGUE

The *Hipparcos* satellite was an ESA-funded astrometric instrument launched in 1989 and operated until 1993. The primary mission was the determination of accurate positions, proper motions, and parallaxes of 118,218 stars. The results of these observations form the *Hipparcos* Catalogue (ESA 1997). The accuracies of the *Hipparcos* astrometric parameters are roughly 1 mas for position, 1 mas yr^{-1} for proper motion, and 1 mas for parallax.

Early in the planning stage for *Hipparcos*, the mission was expanded to include data from the satellite's star mapper. The results of the star mapper's observations are contained in the Tycho Catalogue (ESA 1997) of 1,058,332 objects. The accuracies of the Tycho positions and proper motions are roughly 25 mas for position and 25 mas yr^{-1} for proper motion. In addition to the positional information, the Tycho Catalogue contains two-color photometry for the vast majority of its objects. The precisions of the Tycho photometric data are generally much better than 0.1 mag. A thorough introduction to the *Hipparcos* and Tycho mission can be found in ESA (1997).

4. IMPROVING THE PROPER MOTIONS

The accuracies of the Tycho positions make it the best astrometric database of its size at its mean epoch. However, the positions quickly degrade, because of the uncertainties in the proper motions:

$$\sigma_{x_{t1}} = \sqrt{[\sigma_{\mu x}(t_1 - t_0)]^2 + \sigma_{x_{t0}}^2}\,, \qquad (1)$$

where $\sigma_{x_{t1}}$ is the standard error in coordinate x at epoch t_1, σ_{μ_x} is the standard error of proper motion μ_x, t_0 is the epoch of observation, and $\sigma_{x_{t0}}$ is the standard error of coordinate x at epoch of observation t_0. Using only the Tycho data, the positional errors degrade to 100 mas within 4 years from the epoch of observation (J1991.25). In combining the Tycho and AC positions, the average standard deviation of the proper motion is 2.4 mas yr^{-1} in each coordinate, and 80% of the stars have proper motions determined better than 3.5 mas yr^{-1}. Even using the higher value for the proper-motion error, the positional accuracies will remain under 100 mas for almost 30 yr. For applications such as reducing older plate data (e.g., the Palomar surveys) or current reference star information, the combined AC and Tycho (ACT Reference Catalog) proper motions are required. A graphic demonstration of the improvement that can be attained is shown in Figure 1.

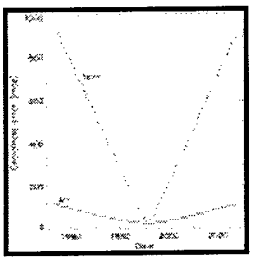


FIG. 1.—Positional errors of Tycho and the combination of AC and Tycho (ACT), by epoch. Positional error of 25 mas and proper-motion error of 25 mas yr^{-1} were used in computing the Tycho curve. Positional error of 25 mas and proper-motion error of 3 mas yr^{-1} were used in computing the ACT curve.

4.1. *Matching Tycho and AC 2000*

In order to make the ACT Reference Catalog of high quality, it was decided that some problematic "stars" would not be used. Positions indicated in the Tycho Catalogue as coming from close multiple stars or those of extremely low astrometric quality were discarded (no stars with "D," "R," or "S" in the "MultFlag" field or with "9" in the *Q*-field were used).

To match the two data sets, the Tycho entries were brought to the AC 2000 epochs by the application of the published Tycho proper motions. An area with a radius of 15″ around each Tycho star was searched. If there was a one-to-one match (i.e., one AC 2000 entry and one Tycho entry in the search area), then the two were identified as the same star. If there was not a one-to-one match (for example, one Tycho entry and two AC 2000 entries), then a ratio of the distances between the Tycho and the closest AC 2000 star and between the Tycho and the farther AC 2000 star was computed. If the value of the ratio was 0.2 or less, and the difference in magnitudes between the Tycho and closer AC 2000 star within 1.5, then the Tycho and the closer AC 2000 star were identified as the same. Otherwise, the matching was considered ambiguous and no cross-identification was made. For the Tycho stars not matched at this point, another search was made, but without application of any proper motions. This was done to find stars whose positions are actually degraded by the application of the Tycho motions. A search area with a radius of 20″ was used. Again, a positional ratio test of 0.2 and a magnitude test of 1.5 were applied for all nonsingular matches. For the Tycho stars still not matched, a search in the NLTT Catalogue (Luyten 1979; Luyten & Hughes 1980) was made. Luyten's proper motions were then applied to the Tycho stars to bring them to the epochs of the AC 2000 positions. A search area with a radius of 15″ around each Tycho star was used. Once again, if more than one star fell within the search area, a ratio test and a magnitude test were used to determine which observations were really the same star. In total, 97.5% nonproblematic Tycho stars were unambiguously matched with an AC 2000 entry.

4.2. *Computation of Proper Motions*

Once the identifications between the AC 2000 and Tycho catalogs were made, the proper motions were computed using the differences in position and epoch. To bring these proper motions from the mean of the Tycho and AC epochs to epoch J2000.0, the application of standard formulae were used (Fricke et al. 1963). In the computation of the foreshortening terms, the radial velocities were taken from the Hipparcos Input Catalogue (ESA 1992) and the parallaxes were taken from the *Hipparcos* Catalogue. It should be noted that the stars in common with *Hipparcos* were treated the same as all

other stars; the proper motions in the ACT Catalog are those computed from the AC and Tycho data. Users wanting the *Hipparcos* data for these stars can simply substitute the information by using the cross-references given in the ACT.

There are scarcely any catalogs available to check the accuracies of the ACT proper motions. This is because few astrometric-quality catalogs are currently on the *Hipparcos* reference frame, and those that are have epochs close to Tycho. In order to give some confidence in the new proper motions, an examination of ACT and *Hipparcos* proper motions for those stars in common can be used. One must realize, however, that these are not independent, uncorrelated data sets, since the AC 2000 was reduced to the *Hipparcos* system using the *Hipparcos* data. However, the method employed in that conversion was designed to remove systematic deviations in the AC 2000; most of the random errors of individual stars should remain (Urban et al. 1998). Typically, about 35 stars in common between *Hipparcos* and the AC were used to correct any one AC observation. For a star in common to the AC and *Hipparcos*, the weighting formula used will allow ≈10% of the final correction to come from the individual difference between the *Hipparcos* and AC 2000 value for that star. This ensures that the AC 2000 positions adhere systematically to *Hipparcos*, but that the positions of individual stars are not highly correlated. Figure 2 shows a histogram of the differences in ACT and *Hipparcos* proper motions. The distribution is well centered around zero, and the standard deviations are 3.8 and 3.5 mas yr^{-1} in right ascension and declination, respectively, about what would be expected given the AC 2000 and Tycho positional accuracies and the difference in epoch.

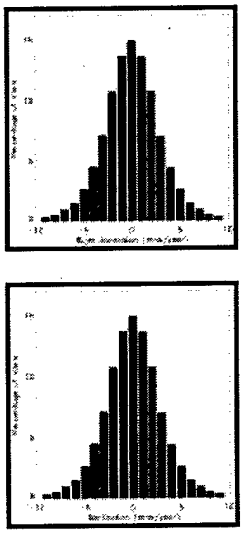


FIG. 2.—Differences in proper motion between the ACT Reference Catalog and *Hipparcos* Catalogue; (*a*) shows the right ascension differences, (*b*) shows the declination differences. Not plotted are data differences larger than ±10 mas yr^{-1}, which total 2% of the data.

4.3. *Computation of Standard Errors of Proper Motion*

The computation of the standard error in proper motions is straightforward, since only two-position proper motions are involved. The formula used is

$$\sigma_\mu = \frac{\sqrt{\sigma_{AC}^2 + \sigma_T^2}}{E_T - E_{AC}}, \qquad (2)$$

where subscripts AC and T refer to the AC 2000 and Tycho data, respectively, σ is the standard deviation of position, μ is proper motion, and E is epoch. Note that σ_{AC} was computed by the scatter in positions of the individual images making up the mean position. In cases in which the star is found on only one AC plate, the mean standard deviation of a single image for that particular AC zone is used. In order not to underestimate $\sigma\mu$ for stars with very small values of σ_{AC}, a lower limit of 80 mas (based on the distribution of AC 2000 errors) has been placed on this value. The distributions of the ACT proper-motion errors are seen in Figure 3.

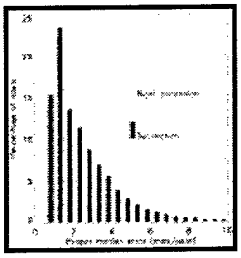


FIG. 3.—Histogram of standard errors in proper motion of the ACT Reference Catalog.

Figure 4 shows the standard errors of the proper motions by equatorial coordinates. The banded structures seen in the plots are caused by the zonal nature of the AC observations; the earlier and more precisely measured zones have lower standard errors than the areas observed later or not well measured. Two of the worst areas are near declinations of +35° and -50°. These correspond to the zones assigned to the Potsdam and Sydney observatories, respectively. Most of the area originally assigned to Potsdam was actually observed in the 1930s and 1940s by other institutions, and thus the epoch difference between the AC and Tycho is smallest here. The Sydney data were generally observed early this century, but the measurements are the poorest of any institution's. Although these are generally the worst areas in the sky, the ACT proper motions in these zones should still be about 5 times more accurate than using Tycho alone.

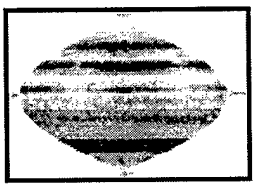
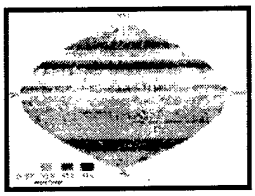


FIG. 4.—Standard errors in proper motion of the ACT Reference Catalog with respect to equatorial coordinates; (*a*) shows the standard errors in the right ascension proper motions, (*b*) shows the same for the declination proper motions.



5. ACT CHARACTERISTICS

The ACT Reference Catalog contains positions, proper motions, and error estimates of 988,758 stars. The positions and proper motions are on the *Hipparcos* system (ICRS) for the epoch J2000.0. The positions are from the Tycho Catalogue (epoch J1991.25), but have been updated using the newly computed ACT proper motions. Photometric data from the Tycho Catalogue are provided. In addition, flags from Tycho indicating astrometric quality, duplicity, and variability are included. Cross-references to Tycho, AC 2000, the Bonner, Cordoba and Cape Durchmusterungs, the Henry Draper Catalogue, and the *Hipparcos* Catalogue are provided. The data are available at the astronomical data centers. In addition, users can contact the author via electronic mail to obtain information on getting the data on CD-ROM.

Positional standard errors from the Tycho Catalogue for epoch J1991.25 are included. Also, an error estimate of the proper motion is given, as computed in the previous section. These two quantities will allow users to compute positional errors for any epoch by a similar computation, as shown in equation (1). In actuality, the date of highest positional accuracy, called the *central date*, is not J1991.25, but slightly earlier. The central date depends on the precision of the Tycho and AC positions (Eichhorn 1974) and is generally within 1.5 yr of the Tycho epoch. Since the goal of this work was to provide new proper motions for the Tycho data and not to recompile positions in the Tycho Catalogue, the central date and its position are not given. The effects on the error computation for epochs earlier than J1991.25 are trivial; generally, it will be overestimated by less than 1 mas.

6. FUTURE WORK

Deriving accurate proper motions for the Tycho stars will be an ongoing task. Having proper motions computed from only two positions, such as those in the ACT, is not an ideal situation, since flaws in either the AC or Tycho, or unmodeled motions—e.g., binary motion—will lead to spurious proper motions. As new observations are made, such as the USNO's CCD Astrometric Catalog (Gauss et al. 1996), or older data are reduced to the *Hipparcos* system, such as the USNO's Twin Astrograph Catalog (Zacharias et al. 1996), they will be added to improve this situation. In addition, there is an IAU working group sponsored by Commissions 8 and 24 assigned to investigate remeasuring the Astrographic Catalogue plates. If some of the worst zones are remeasured, then a new reduction of the AC data is in order and can help alleviate some of the disparity seen in Figure 4. Until one or all of the above are completed, the current combination of AC and Tycho positions will remain the best source of proper motions for the Tycho stars.

7. SUMMARY

The successful *Hipparcos* mission has given the astronomical community a wealth of data, especially in the area of astrometry. The Tycho Catalogue provides accurate positional and photometric data for 1 million stars; however, the proper motions it contains need to be recomputed if the positions are to remain accurate over decades. The USNO has computed new proper motions for the vast majority of the Tycho stars by combining the Tycho positions with those of the recently released AC 2000 catalog. This new catalog, called the ACT Reference Catalog, contains astrometric data and includes Tycho photometry, flags, and cross-references.

We would like to extent our gratitude to all those at the USNO who worked on the data preparation and reduction of the AC 2000. A special note of thanks is given to F. Stephen Gauss, director of the Astrometry Department, who recognized that workers need good tools and thus provided high-quality hardware and software without which this project would have been impossible. We would be remiss if we did not thank the Tycho Consortium, and especially Erik Høg, whose years of hard work ensured the superlative quality of the Tycho positions.

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